

# Mechanical and Chemical Evolution of Simulated Fault Gouge

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## *Non Technical Summary*

We are investigating the interaction of mechanical comminution and chemical healing of simulated fault gouge. Reactivation of mature active fault zones is accompanied by localized fracturing yielding a distribution of particle sizes. This gouge zone is where fault displacement is accommodated. The interaction of this gouge with interstitial aqueous fluid at hydrothermal conditions results in a healing or re-lithification of the gouge by several processes, among them pressure solution and Ostwald ripening. This healing influences the porosity, permeability, cohesive strength, and other properties of the gouge zone that will influence fault strength and "time-to-fracture". The "Dietrich Law" has been the cornerstone of our understanding of fault zone friction. Its strength lies in its reproducibility over a range of experimental set-ups and laboratories. However, effects of fluid-rock interaction in the fault zone or gouge at temperatures typical of the upper crust are not generally obvious from such friction experiments. Yet, this is central to the issue of fault zone evolution and reactivation.

We present data on 1-2 month long, hold-slide-hold experiments using artificial monomineralic gouge. These experiments indicate healing and development of cohesive shear strength in the gouge over time. The importance of thermally activated chemical processes is suggested by absence of healing in dry experiments. Pressure solution, Ostwald ripening and cementation are key mechanisms that are involved in this process of healing. We also present new data on the hydrostatic volumetric creep of monomineralic aggregates, identifying the cooperation of two creep mechanisms that are operative during time dependent compaction. Results of Ostwald ripening experiments are also shown, as an example of reaction transport modeling parameterized by experiments.

## *Introduction*

Two schools of thought exist on crustal seismogenesis. In one, earthquakes are thought of as slip events on existing fault zones such as those occurring on the San Andreas Fault system. Earthquakes have also been described in terms of failure or rupture of intact rocks at depth. The two ideas have evolved as a result of two different types of

laboratory experiments. The former has resulted in the well known "Dietrich Law" of rate- and state- variable friction developed from sliding friction experiments either in double direct shear, triaxial, or even in rotary shear configurations. The latter has evolved from triaxial deformation experiments on intact crystalline rocks often complemented with acoustic emission during deformation. It is possible that both of the above experimental styles capture certain and essential parts of seismogenesis. However, a large part of the rate- and state- variable friction laboratory work was performed with bare rock surfaces, at room temperature, and over limited time duration (minutes to hours). In nature, on the other hand, fault reactivation occurs at depths and elevated temperatures, fault surfaces are usually coated with rock flour (fault gouge), and the slip characteristics change over a wide range of time scales. Central to the issue of fault reactivation is the mechanical role of fault gouge that accommodates the displacement along the fault. Work of Johnson et al. (1994) on surface expression of the M7.5 Landers earthquake and Chester and Logan (1986) on the Punchbowl fault zone have revealed the complex nature of fault zones. It is known from the above studies and others that fault slip is not accommodated within one quasi-planar fault surface but along numerous small shear zones within a fault zone that may be distributed over hundreds of meters. Also, the fault rocks within such zones are comminuted and "heal" in the presence of hot fluids over time. Fault zone strength may approach that of country rock over general interseismic periods of decades to centuries (a time scale amenable to recurrence of major California earthquakes). Time-dependent chemical processes such as pressure solution (and Ostwald ripening) driven by presence of reactive fluids and high temperatures drive mass transfer over the scale of fault zones and result in cementation and at least partial recovery of fault strength (Chester and Logan, 1986; Sibson, 1987). We attempt to simulate such processes in the laboratory, as we now discuss.

### ***Investigations Undertaken***

During this past year we have performed the following tasks:

- Hydrostatic Creep Experiments of Gypsum, Quartz, and Calcite Aggregates
- Triaxial Hold-Slide-Hold Experiments using quartz, calcite, and gypsum gouge
- Ostwald Ripening Experiments With Quartz Gouge
- Initial Reaction Transport Modeling of Gouge Healing

### ***Results***

#### **Gouge Creep Experiments**

This experiments are conducted under hydrostatic loading conditions, with relatively large samples, in order to parameterize the time dependent behavior of bulk porous monomineralic aggregates. We are focusing this effort on parameterizing creep behavior in terms of particle size distribution, in addition to the variables of effective pressure, temperature, grain size and volume strain as in previous work.

In monomineralic aggregates at low stresses, high temperatures, and large volume strains (just how high, low, or large depends on the mineral), we have found that creep behavior may be characterized by the following creep laws, shown by example for a narrowly distributed particle size distribution with quartz (from Dewers and Hajash, 1995) and crushed gypsum aggregates with a wider distribution (de Meers and Spiers, 1995):

$$\epsilon - \epsilon_0 = 0.020 \ln \left\{ 1 + \frac{0.0025e}{d^{1.9}} (e^{0.007P} - 1)(t - t_0) \right\}$$

$$\varepsilon - \varepsilon_0 = 0.018 \ln \left\{ 1 + \frac{0.00076 e^{-55.0 \varepsilon_0}}{d^{1.708}} (e^{1.16 P_t} - 1)(t - t_0) \right\}$$

These models reproduce experimental data to an excellent degree of correlation ( $R = .96$  for gypsum and  $.98$  for quartz). We show this here as an argument for using gypsum as an analogue for quartz behavior, because of gypsums greater solubility and precipitation/dissolution rates when compared with quartz at temperature below 200 degrees C. Essentially the pressure solution behavior of gypsum under certain conditions (i.e., low stresses) mimics that of quartz, but the healing kinetics are much more amenable to laboratory investigation.

We have found that several parameters, in particular the exponential term involving volume strain, is a strong function of particle size distribution, and we are finishing a series of experiments designed to delineate the creep dependence on properties (moments) of the particle size distribution. This will enable us to construct models of fault gouge healing by pressure solution, as a function of the distribution of gouge sizes resulting from fault rupture.

In addition, by examining creep behavior over a range of temperatures, stresses, and initial loading conditions we can distinguish (at least crudely) between mechanisms from creep data alone. An example of this is calcite creep, as shown in the following figures.

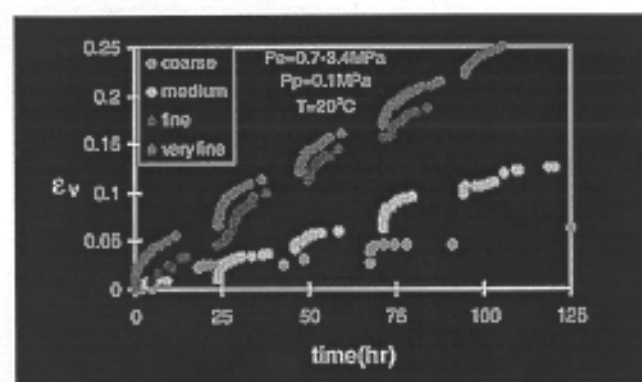


Figure 1: Volumetric Creep of calcite aggregate under low hydrostatic load

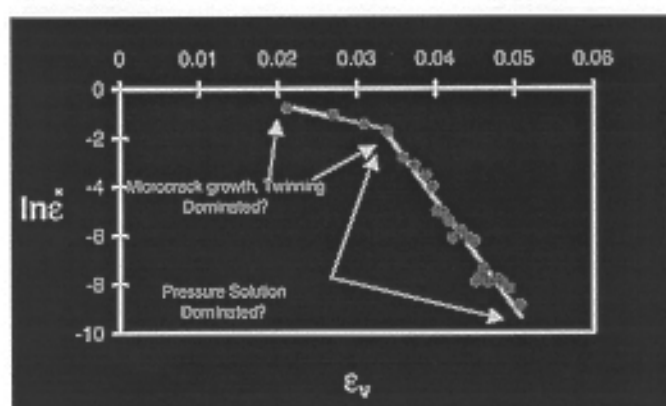


Figure 2: Mixed mode volumetric creep under hydrostatic load. A transition from microcrack growth-controlled creep to pressure solution-limited creep is evident in an inflection and change in slope on a  $\ln(\text{strain rate})$ -strain plot.

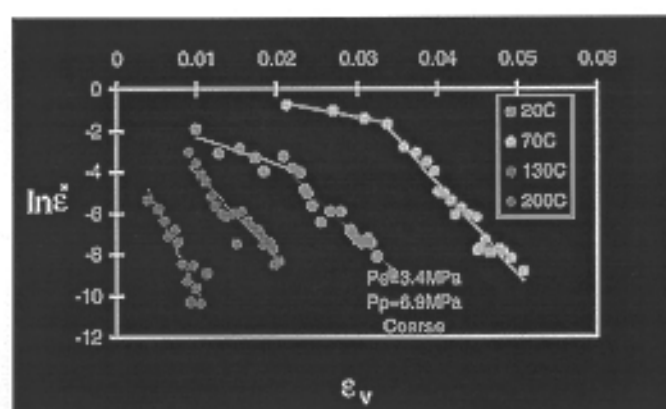


Figure 3: Mixed mode creep is evident at lower temperatures, but is lost at higher temperatures, basically showing the dominance of pressure solution mechanism at higher temperature. One possible reason for the lower strain rates at higher temperatures is the retrograde solubility of calcite in water.

In Figure 1, we show a creep behavior in calcite aggregates that is consistent with the models for quartz and gypsum shown above. However, at higher stresses and lower temperatures, a mixed mode behavior is evident. Creep due to sub critical crack growth (with or without healing) is known to increase with the logarithm of time, and we have shown previously that creep associated with a pressure solution or solution transfer mechanisms also increases with the logarithm of time (this is evident in the above creep laws in the negative exponential dependence on strain). When presented on a plot of  $\ln(\text{strain rate})$  versus strain, this  $\log(\text{time})$  dependence is evident as a linear spread of data. This is shown in Figure 2, for the case when crack growth is dominant at low strains and higher stresses. A shift in dominant mechanism is evident as a "dog-leg" in the data, with pressure solution dominating at larger strains, lower stresses and higher temperatures. Figure 3 shows that the "dog-leg" is absent as temperature increases. The different mechanisms are also evident in the grain size dependence, and when both operate in parallel, the resulting creep behavior can be rather confusing to deal with. We are in the process of deriving creep laws for this mixed mode behavior. While shown for

calcite, such a mixed mode behavior is probably a realistic model for feldspar deformation (Hajash et al., 1998) and so may be important for wet fault creep in granitic host rocks.

#### Hold-Slide-Hold Experiments Using Gouge-Filled Sawcuts

A series of long term (1 month or longer) triaxial hold-slide-hold experiments have been conducted using calcite (room temperature), gypsum (room temperature), and quartz (150-200 degrees). Our most successful experiments, i.e. those showing the most dramatic changes, have been using gypsum gouge, as shown in the following figures.

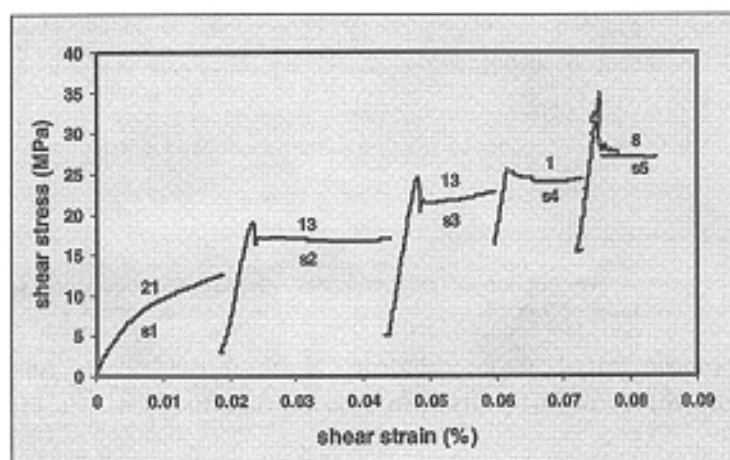


Figure 4: Shear-stress strain plot for hold slide hold test using Berea Sandstone sawcuts with gypsum gouge in the presence of aqueous pore fluid. "sx" denotes slide periods; hold periods in between range from 1 day to one month. Note the increase in shear strength and sliding friction. There is no stress drop for the slide period s4 when the hold period was 1 day.

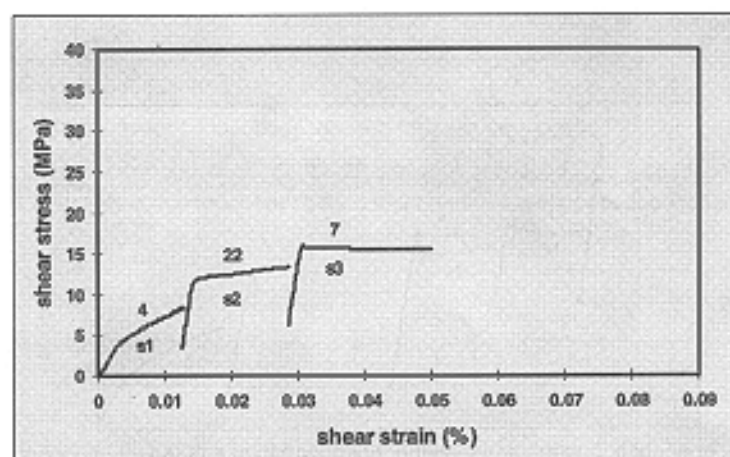


Figure 5: Similar to Figure 4, except in the absence of aqueous pore fluid. Note the lack of development of any cohesive shear strength, and the total lack of stress drop, when compared to Figure 4.

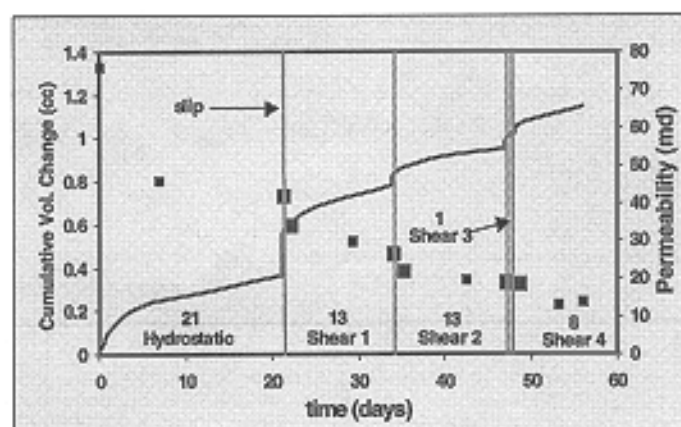


Figure 6: Evolution of porosity (pore volume change) and permeability for hold-slide-hold test shown in Figure 4.

Significant "healing" of the gouge evident from the loss of porosity and permeability and also in the increase of shear strength accompanies gouge exposed to relatively long times in the presence of water. This is due to the operation of solution transfer or pressure solution processes and Ostwald ripening.

Effort are under way to characterize the evolved gouge in these experiments both in terms of particle size distribution but also using electron microscopy.

#### Evolution of Gouge Particle Size Distribution

Additional experimental effort has been directed toward the operation of Ostwald ripening in the evolution of particle size distribution of gouges. Experiments have been conducted using calcite, gypsum, and quartz gouge under zero effective pressure, hydrostatic loading at effective pressure, and under triaxial loading. We are still in the mode of characterizing the run products of these experiments. However we are also attempting to model the evolution of gouge psd with numerical reaction transport modeling. Below is an example of the change in quartz gouge distribution with time at 200 degrees C and under zero effective pressure conditions. The model was parameterized from experimental data.

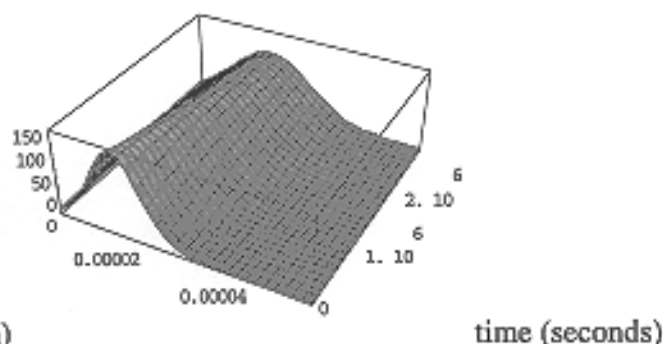


Figure 7: Evolution of artificial quartz gouge particle size distribution due to Ostwald ripening.

This ripening involves dissolution of the finer "tail" of the fraction, produced initially by grain comminution, and accompanying growth of the coarser portions. As a result, with time the mean of the distribution moves to the right (i.e. coarsens) while the distribution



gets wider, and flatter. This is evident in the increase of both the mean and standard deviation of the particle size distribution, as shown in Figure 8 below.

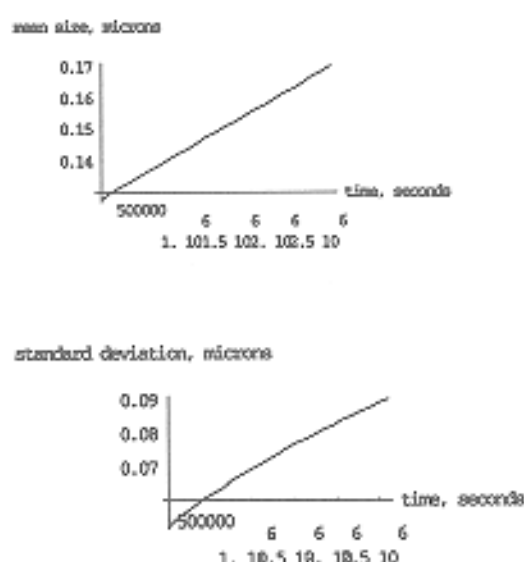


Figure 8: Changes in mean grain size and standard deviation with time for quartz gouge (produced by crushing in a ball mill) at 200 degrees C and 2000 psi pressure.

#### Continuing Work

In the spirit of the above, we are continuing with new experiments that test the differences in behavior that occur from gouge exposed to the same extrinsic conditions but with different size distributions. This will enable the extension of volumetric creep laws to include influences made by the shape of the particle size distribution, and also to correlate differences in evolution of shear strength or gouge coherence and porosity and permeability to the evolution of an initial gouge particle size distribution.

#### Publications

- Muhuri, S., and Dewers, T., 1999, Strength and permeability in synthetic fault zones: EOS 80.
- Muhuri, S., and Dewers, T., 1999, Wet creep of granular calcite aggregates under upper crustal conditions: Geological Society of America Abstracts With Programs 31, pp. A-57.